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NASA TM X-71757

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(NASA-TM-X-71757) THE 7.5 kW SOLAR ARRAY  
SIMULATOR (NASA) 11 p HC \$3.25 CSCL 14B

N75-27018

Unclassified  
28672

## 7.5 KW SOLAR ARRAY SIMULATOR

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TECHNICAL PAPER to be presented at  
Eleventh Propulsion Conference cosponsored by  
the American Institute of Aeronautics and Astronautics  
and the Society of Automotive Engineers  
Anaheim, California, September 29 - October 1, 1975

## 7.5 KW SOLAR ARRAY SIMULATOR

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### Abstract

A high power solar array simulator capable of providing the input power to simultaneously operate two 30 cm diameter ion thruster power processors was designed, fabricated, and tested. The maximum power point may be set to between 150 and 7500 watts. This represents an open circuit voltage from 50 to 300 volts and a short circuit current from 4 to 36 amps. Illuminated solar cells are used as the control element. The illuminated solar cells provide a true solar cell characteristic and permit the option of simulating changes in this characteristic due to variations in solar intensity and/or temperature of the solar array. This is accomplished by changing the illumination and/or temperature of the control cells. The response of the output to a step change in load closely approximates that of an actual solar array.

### Introduction

Power processors<sup>(1)</sup> for 30 cm diameter ion thrusters<sup>(2)</sup> are designed to operate from a solar array power source. Engineering studies defining the solar array requirements and operating characteristics have been documented for a variety of missions. A solar array simulator (SAS) provides a convenient means for dynamic ground tests of a complete system of thruster, power processor, and solar array.

To provide meaningful data on interactions between one or more power processors and the solar array, it is necessary that the response of the SAS to changes in load closely simulate that of an actual solar array.

Using illuminated solar cells as the control element for the SAS offers some unique capabilities. The output curve of the SAS can be modified to represent changes in illumination and/or temperature of an array simply by changing the illumination and/or temperature of the control cells. Other variations that occur in solar arrays can also be simulated by making the respective change in the control cells. Solar cells identical to those in the actual solar array can be used as the control cells, providing an output curve identical to that of the actual solar array.

The final design, described in this paper, has fast dynamic response, its characteristics can be readily modified to simulate changes in the environment, and resulted in a low cost compact unit.

### Apparatus

#### Mechanical

A photograph of the solar array simulator is shown in Fig. 1. The simulator is contained in one rack except for the DC power supply. The bottom of the rack contains 40 water cooled transistor modules; 7 driver modules and 33 output modules. Each module consists of a printed circuit board, a 0.318 cm thick water cooled copper heatsink, 10 parallel

transistors with associated resistors, and two fuses. A typical module is shown in Fig. 2. The modules plug into printed circuit edge connectors to facilitate assembly and replacement. The upper portion of the rack contains the control electronics and indicator lights that identify blown fuses.

The SAS requires 0.316 liters/sec of cooling water to maintain the case temperature on the transistors at less than 60° C.

#### Electrical

The functional diagram of the complete circuit is shown in Fig. 3. The output circuit operates as a dissipative voltage regulator which follows the reference input to the open circuit voltage ( $V_{oc}$ ) adjust control. The reference circuit generates the V-I characteristic curve that drives the output regulator. A voltage across shunt R10 proportional to the current in the output load is applied to the short circuit current ( $I_{sc}$ ) adjust control. The  $I_{sc}$  adjust control scales this signal and applies it to the input of amplifier A1. A1 is a variable load, across the control solar cells, proportional to the current in the output load. Amplifier A2 measures the voltage across the solar cells and provides a reference signal to the output circuit proportional to this voltage. This reference signal corresponds to the required output voltage for the specified load current as defined by the solar array V-I characteristic curve.

The schematic diagram of the output circuit is shown in Fig. 4. Amplifier A3 is an integrator and summing junction for the output circuit feedback loop. The integrator also stabilizes the loop. Amplifier A4 inverts the signal. The power output consists of four stages of current amplification capable of delivering a load current of 40 amps. Capacitor C8 is used to dampen internal oscillations in these stages. Transistors Q1 thru Q400 are mounted in groups of 10 on water cooled copper heat sinks which are integral parts of the printed circuit boards. Each board also contains individual base and emitter resistors for each transistor. Each board has a fuse in both the base drive and the emitter output lead. If a transistor fails in a shorted condition, these fuses open and remove that board from the circuit. The system will then continue to operate on the remaining boards.

The output circuit transistor (Q1 thru Q402) was chosen for its low cost, availability, and current rating at 300 volts. It has a current capability of 120 milliamps at a collector to emitter voltage of 300 volts.

The reference circuit schematic diagram is shown in Fig. 5. The four solar cells in series were 0.4 cm by 1.0 cm, N on P, 10 ohm-cm silicon cells with a short circuit current rating of 10mA. The cells were chosen for their low value short circuit current, their representative characteristic curve, and their availability. Any type of

solar cell can be used in the circuit, however, Al must be capable of sinking the short circuit current from the cells. The four cells in series provide an open circuit voltage of approximately 2.2 volts. Solar cell illumination is provided by an incandescent DC light source, variable in intensity from zero to 140 mW/cm<sup>2</sup> on the cells. The temperature of the cells is controlled by a variable temperature heatsink. Capacitors C1, C2, and C3 stabilize the SAS.

#### Instrumentation

Static DC measurements of voltage and current were made with the SAS panel meters. These meters have an accuracy of 2 percent of full scale. The transient response of the SAS for a step change in load was measured with a 18 MHZ bandwidth dual-beam oscilloscope. The output current was measured using a precision non inductive 0.1 ohm resistor. A step change in load was generated using a mercury relay to short out part of the load resistor.

#### Results and Discussion

##### Design Stability

The major problem encountered in the design of the SAS was to stabilize the output. Design criteria dictated that the response of the SAS to a step change in load closely approximate that of an actual solar array, assumed here to be nominally 100  $\mu$ sec. At the same time it needed to be stabilized to operate on a curve of widely varying slope and for a load impedance from zero to infinity.

The characteristic curve of the four series solar cells used as the control element is shown in Fig. 6. This is the characteristic that the output of the solar array simulator must duplicate over a range of output short circuit currents ( $I_{sc}$ ) and open circuit voltages ( $V_{oc}$ ). The four operating conditions that give rise to the highest loop gains and hence the severest stability problems are:

1. Maximum  $V_{oc}$  where the voltage across the four control cells requires the largest amplification to obtain the output voltage.
2. Minimum  $I_{sc}$  where a given change in current causes the largest change in voltage.
3. The constant current portion of the curve where the slope is steepest and a small change in current causes a large change in voltage.
4. Load impedances approaching zero where a given change in voltage causes an increasingly large change in current.

If the SAS can be stabilized for these conditions, it should be stable for all others.

The SAS can be stabilized for all of the above conditions by making capacitor C2 of Fig. 5 sufficiently large (0.03  $\mu$ f). However, this results in a response time of greater than 50 msec to a step change in load which is considerably slower than the 100  $\mu$ sec assumed for an actual array. For C2 equal to 300  $\mu$ f the SAS is stable for all operating points greater than 25% of  $V_{oc}$  (Fig. 7) and results in a response to a step change in load that closely approximates the 100  $\mu$ sec time response. This was considered an appropriate compromise between response and stability. The inability to operate at less than 25% of  $V_{oc}$  is not a problem since almost all solar arrays are operated at a

voltage above the maximum power point. For a high quality solar array the maximum power point should correspond to a voltage of greater than 70% of  $V_{oc}$ . Therefore, there is a wide margin between the SAS operating area and the area where instability may occur.

#### Test Results

Figure 8 is a plot of typical static output curves for the SAS including the curves for maximum and minimum power. The maximum and minimum power curves bound the range of operating conditions that can be simulated, along with the provision that the operating point must be above 25% of the  $V_{oc}$  selected. Both  $V_{oc}$  and  $I_{sc}$  are continuously adjustable within their operating range and can be varied independently.

Figure 9(a) is an oscilloscope trace of the response of the control cells to a step change in load from open circuit to 140 ohms. The upper trace is the voltage across the load and the lower trace is the current through the load. Response time of both the voltage and the current was within 15  $\mu$ sec. Figure 9(b) shows the response for a step change in load from 210 ohms to 140 ohms. In this case the response time was within 10  $\mu$ sec. These control cells were tested externally to a step change in load and not as part of the SAS. Figure 10 shows the transient response of the SAS to equivalent step changes in load. Figure 10(a) is for a step change in load from open circuit to 20 ohms and figure 10(b) is for a step change in load from 30 ohms to 20 ohms. The SAS was adjusted for a  $V_{oc}$  of 300 volts and an  $I_{sc}$  of 10 amps. The response time of the SAS to these changes is approximately 10 times slower than that of the control cells alone. This slower response time can be explained by scaling the output capacity of the control cells to that of an actual array. If the 4 control cells in series have an output capacitance of  $C_1$ , a  $V_{oc}$  of 2.2 volts, and an  $I_{sc}$  of 10 mA, then it would require 136 sets of the control cells in series and 1000 sets in parallel to obtain an array with  $V_{oc}$  of 300 volts and  $I_{sc}$  of 10 amps. The array would have an output capacitance of  $(1000/136)C_1 = 73.5C_1$ . Looking at the time constant consisting of the capacitance of the solar cells and the load resistance results in:  $\tau_1 = 140C_1$  for the control cells and  $\tau_2 = 20 \times 73.5C_1 = 1470C_1$  for the array. Thus, the response time for the array should be approximately 10 times slower than that of the control cells. Therefore, the response of the SAS (140  $\mu$ sec) is a good approximation of an actual array (100  $\mu$ sec).

Figure 11 is a plot of the path followed by the output of the control cells in going from open circuit to 140 ohms. This is superimposed on the static DC output characteristic. The overshoot in current is due to cell capacitance. Figure 12 is a plot of the path followed by the SAS for a step change in load from open circuit to 20 ohms. The two paths are similar although the SAS path shows some additional effects of the control loops. The initial dip in the SAS path at the 5  $\mu$ sec point (Fig. 12) is due to the response of the output circuit alone to the step change in load. The loop in the path at the 80  $\mu$ sec point is due to a slight undershoot of the SAS to the step change in load.

Figure 13 is the path followed by the control cells for a step change in load from 210 ohms to 140 ohms and Fig. 14 is the path followed by the

SAS for a step change in load from 30 ohms to 20 ohms. Again the two paths are very similar.

Certain operating regions outside the normal range can be accommodated by derating either the voltage or current capability. It should be possible to simulate arrays with open circuit voltages higher than 300 volts by limiting  $I_{sc}$  to lower currents since the output transistors used can support 700 volt operation at an  $I_{sc}$  of 10 amps. It should also be possible to simulate solar arrays with currents above 36 amps by limiting  $V_{oc}$  to lower voltages since the output transistors are rated for 220 amp operation at 100 volts.

One difficulty with the SAS design is that capacitive loads of greater than  $0.02 \mu F$  can cause oscillations. This should not be a problem in the intended application since the input of the 30 cm diameter ion thruster power processor looks inductive.

#### Conclusion

A 7.5 kw solar array simulator was designed, fabricated, and successfully tested. The maximum power point may be set to between 150 and 7500 W's. This represents an open circuit voltage from 50 to 300 volts and a short circuit current from 4 to 36 amps.

The design uses four 12" illuminated solar cells in series as the control element. The illuminated solar cells provide a true solar cell control characteristic, and also provide the option of simulating changes in this characteristic due to variations in solar intensity and/or temperature of the solar array by adjusting the illumination and/or temperature of the control cells. Changes to the array other than solar intensity and temperature can also be simulated in the same manner.

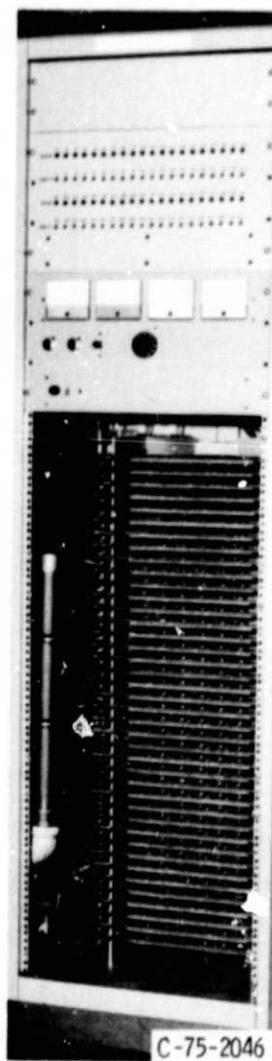
The output impedance of the SA closely approximates that of an actual solar array. This is indicated by the response time and the dynamic path of the output to a step change in load closely approximating that of an actual solar array.

Thus, the solar array simulator generates an output which accurately represents the actual solar array characteristics for the intended application, and should be a valuable tool in the ground testing and evaluation of power processors for 30 cm diameter ion thrusters.

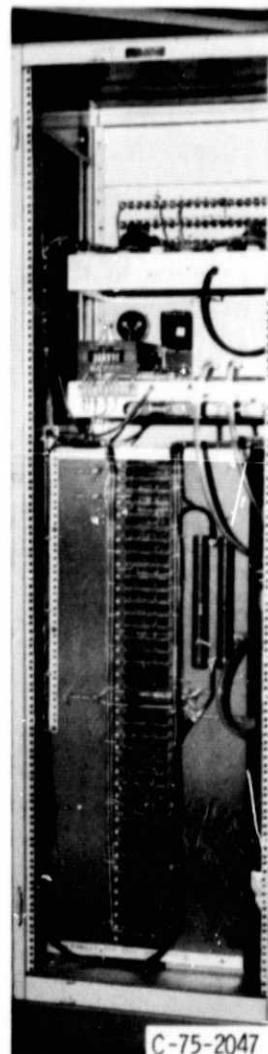
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2. Sovey, J. S., and King, H. J., "Status of 30 Centimeter Mercury Ion Thruster Development," AIAA Paper 74-1117, San Diego, Calif., 1974.

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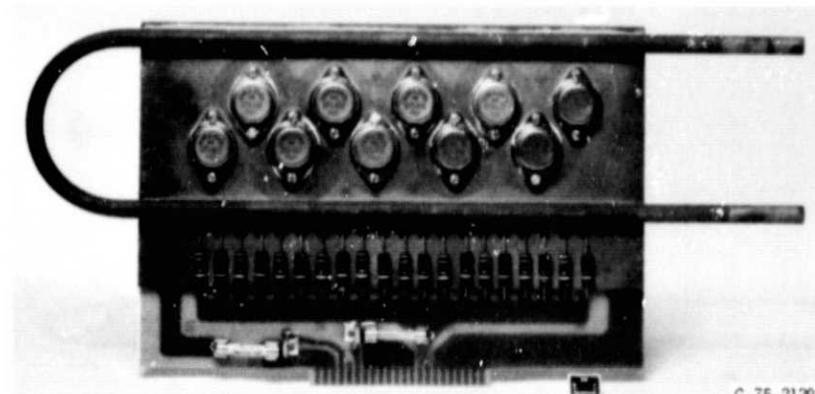
(a) FRONT.



(b) REAR.

Figure 1. - Solar array simulator.

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Figure 2. - Water-cooled transistor module.

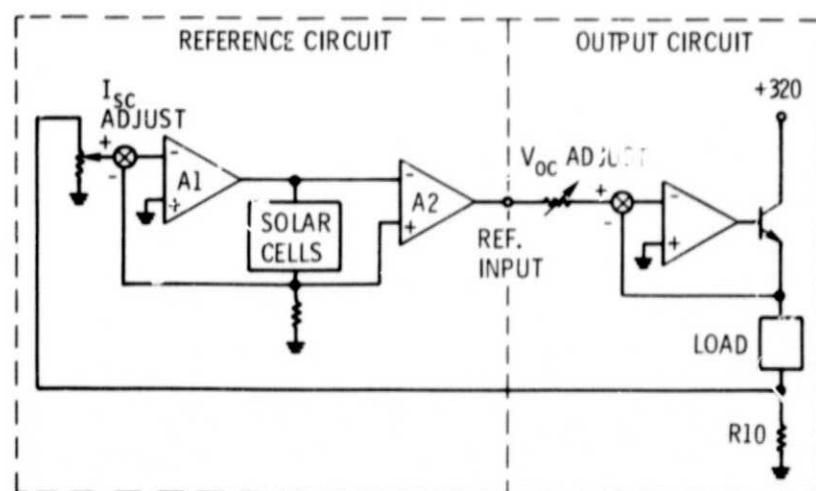


Figure 3. - Functional diagram of the solar array simulator.

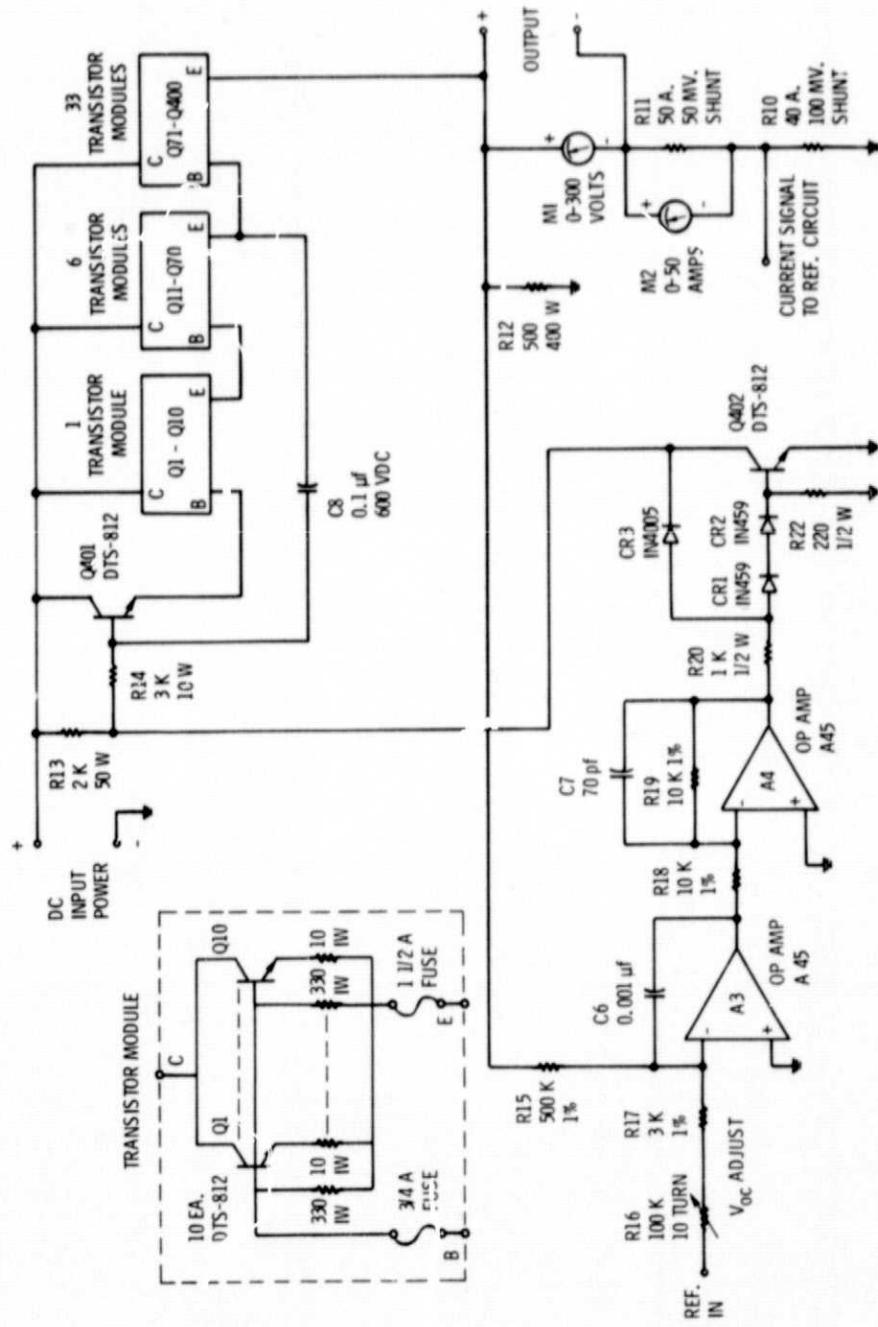


Figure 4. - Output circuit schematic.

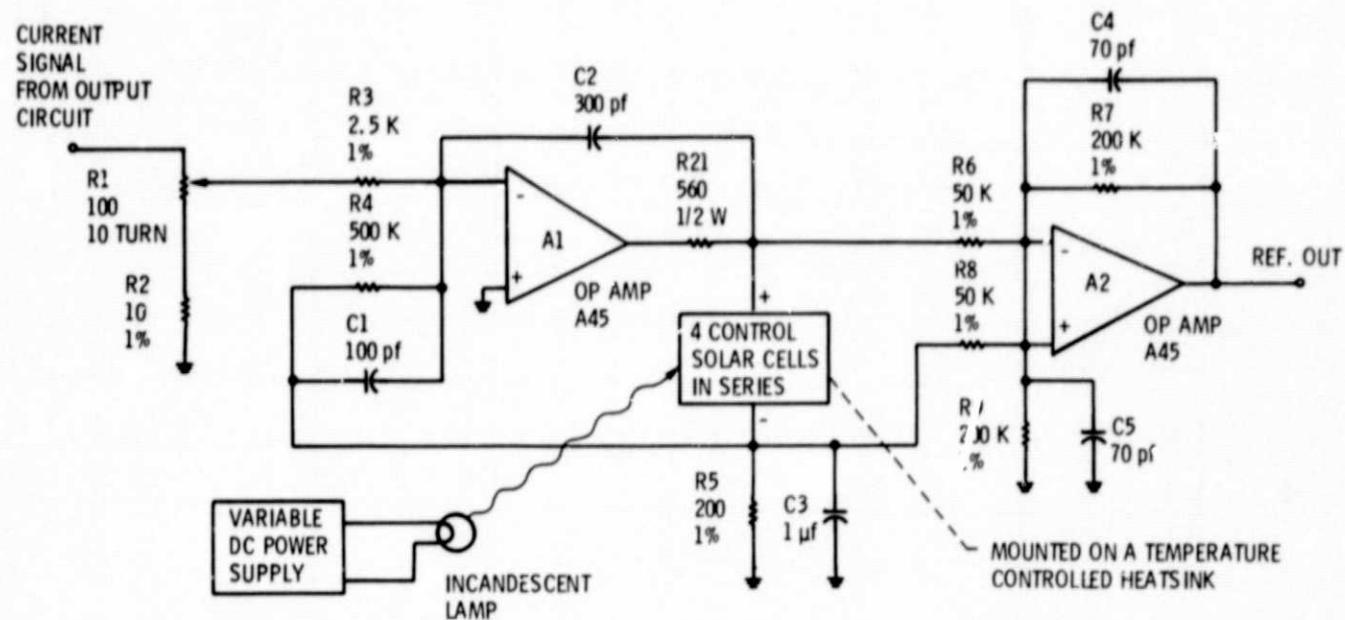


Figure 5. - Reference circuit schematic.

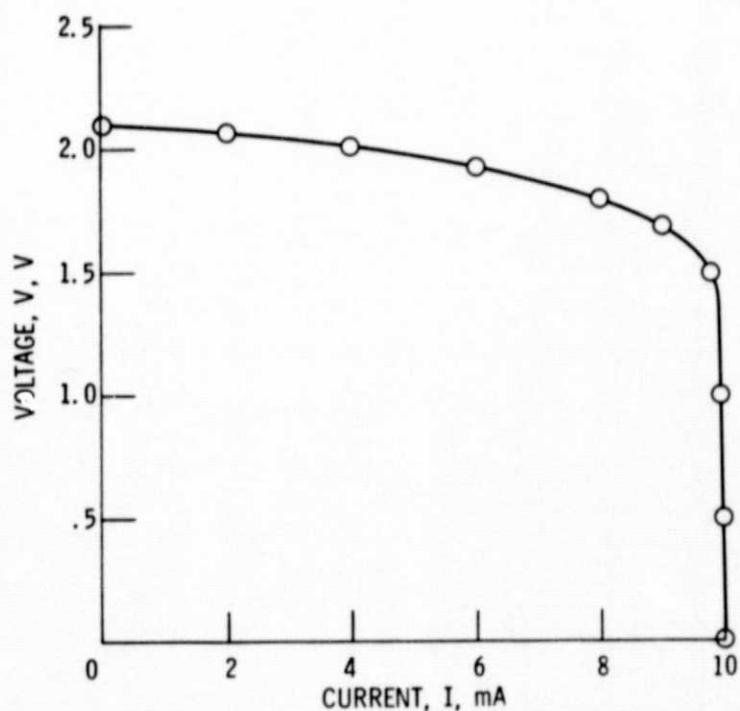


Figure 6. - Characteristic curve of the 4 series control cells. Each cell is  $0.4 \times 1.0$  cm, N on P, 10 ohm-cm, silicon.

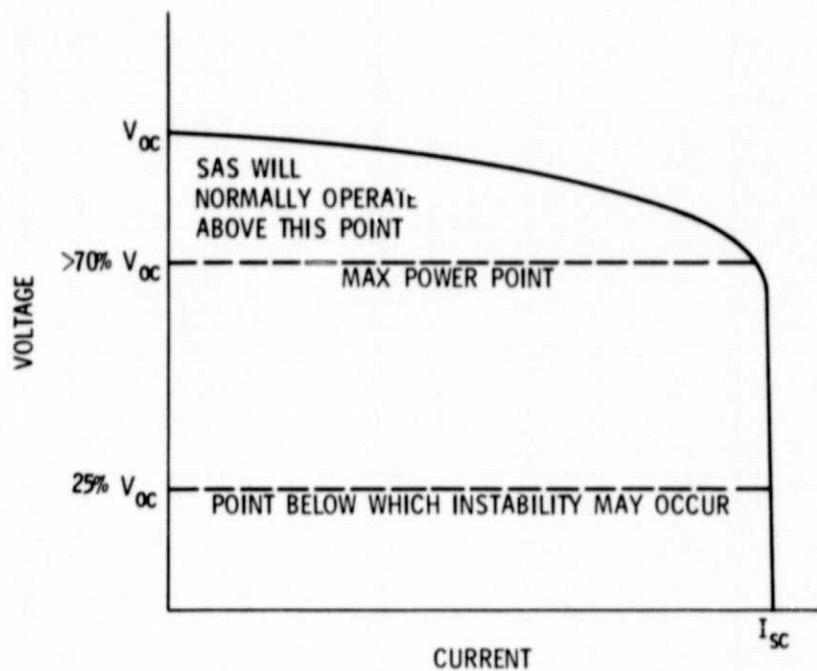


Figure 7. - Curve showing where the SAS will normally operate and where instability may occur.

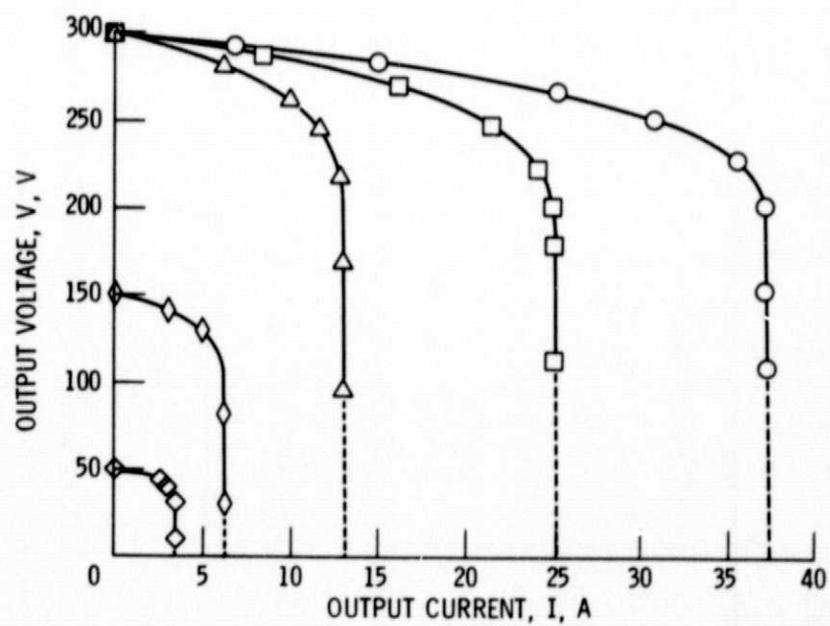
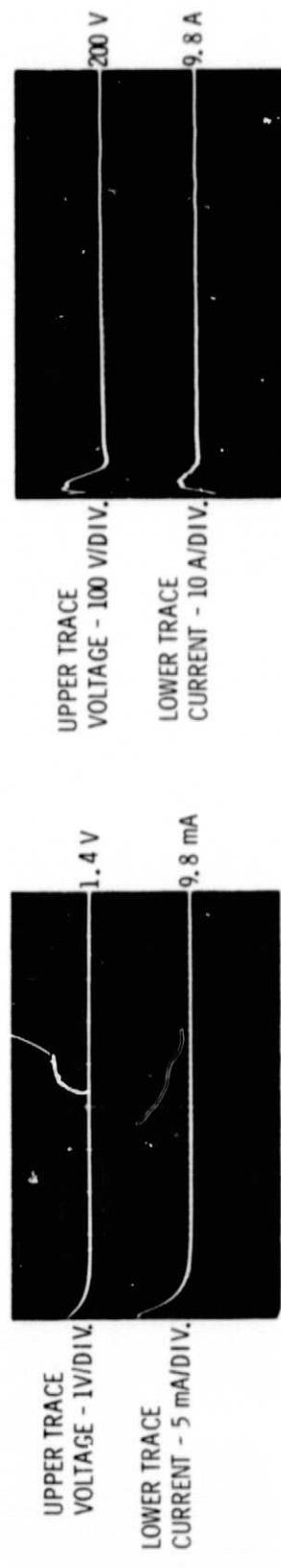


Figure 8. - Typical output curves for the solar array simulator.



(a) STEP CHANGE FROM OPEN  
CIRCUIT TO 140 OHMS.



(b) STEP CHANGE FROM  
210 OHMS TO 140 OHMS.  
210 OHMS TO 140 OHMS.

Figure 9. - Transient response of the control cells to a step change  
in load.  $V_{oc} = 2.1$  volts,  $I_{sc} = 10.0$  milliamps.

SWEET - 100  $\mu$  SEC/DIV.  
(a) STEP CHANGE FROM OPEN  
CIRCUIT TO 20 OHMS.

SWEET - 100  $\mu$  SEC/DIV.  
(b) STEP CHANGE FROM  
30 OHMS TO 20 OHMS.

Figure 10. - Transient response of the output of the SAS to a step change  
in load.  $V_{oc} = 300$  volts,  $I_{sc} = 10.0$  amps.

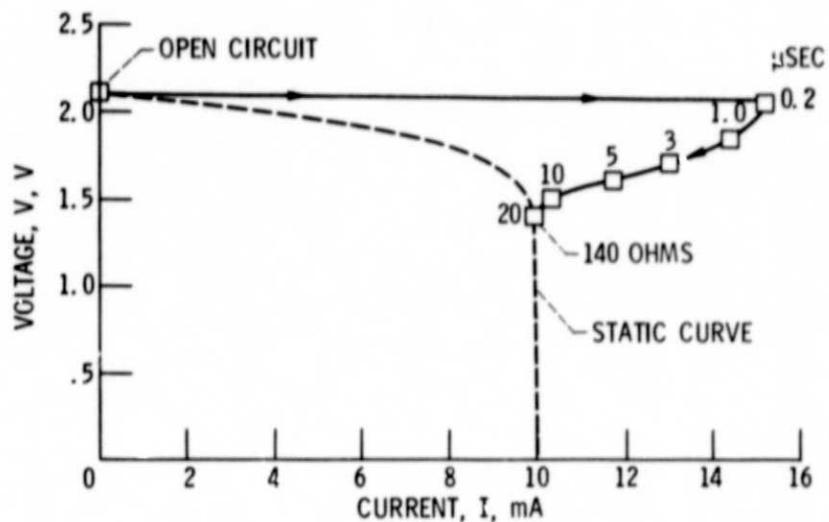


Figure 11. - Path followed by the output of the control cells for a step change in load of open circuit to 140 ohms.

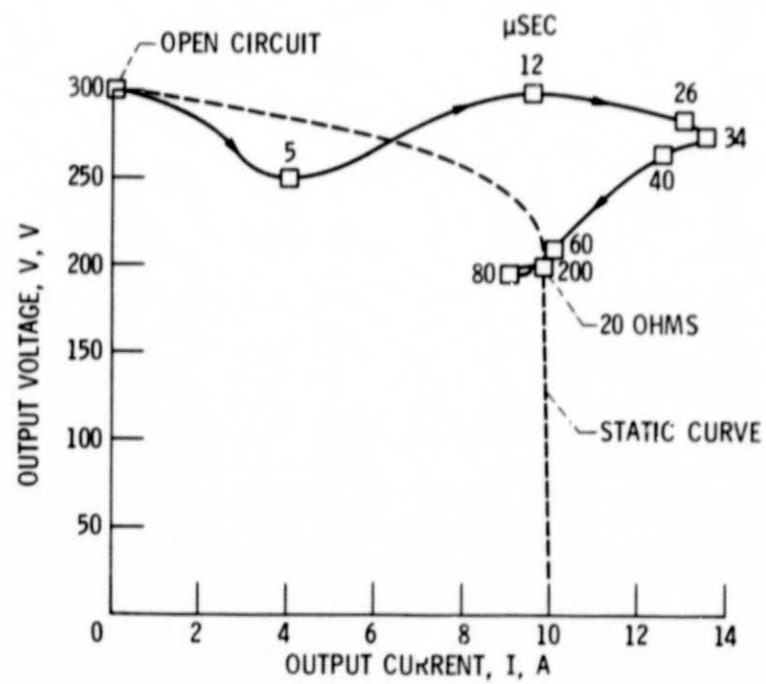


Figure 12. - Path followed by the output of the SAS for a step change in load of open circuit to 20 ohms.

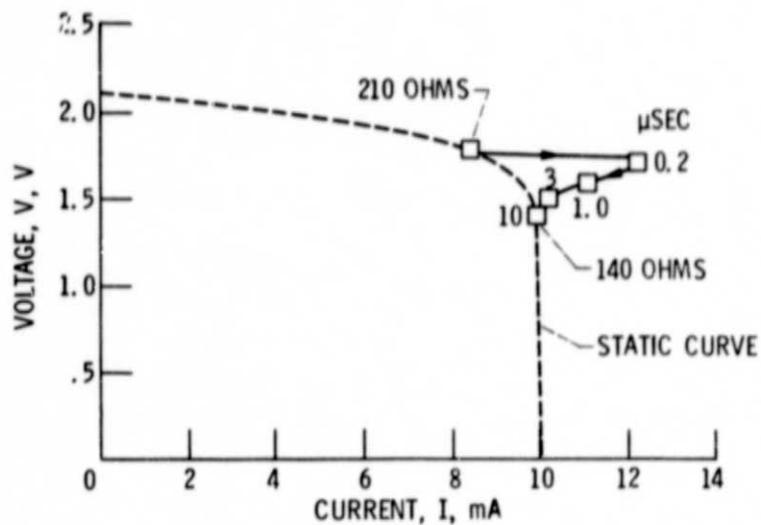


Figure 13. - Path followed by the output of the control cells for a step change in load of 210 to 140 ohms.

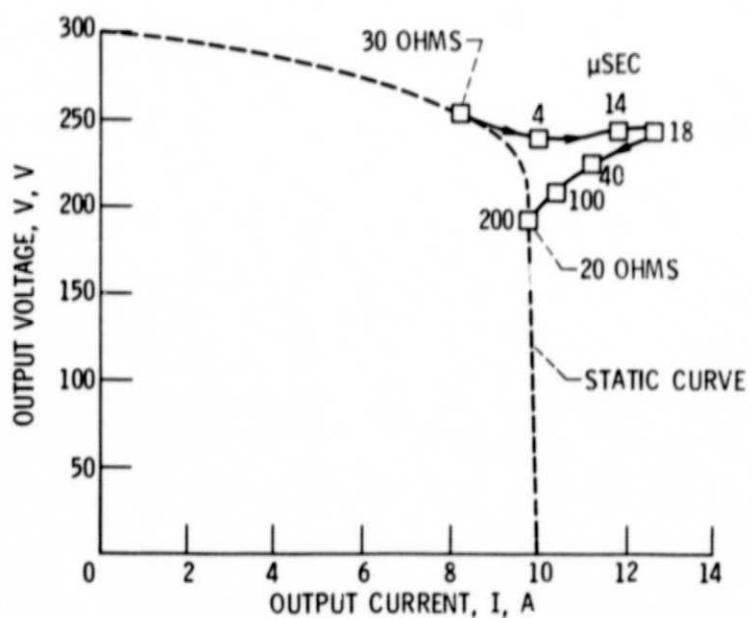


Figure 14. - Path followed by the output of the SAS for a step change in load of 30 to 20 ohms.